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News from the ONSEN PXD readout system

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01.10.2024

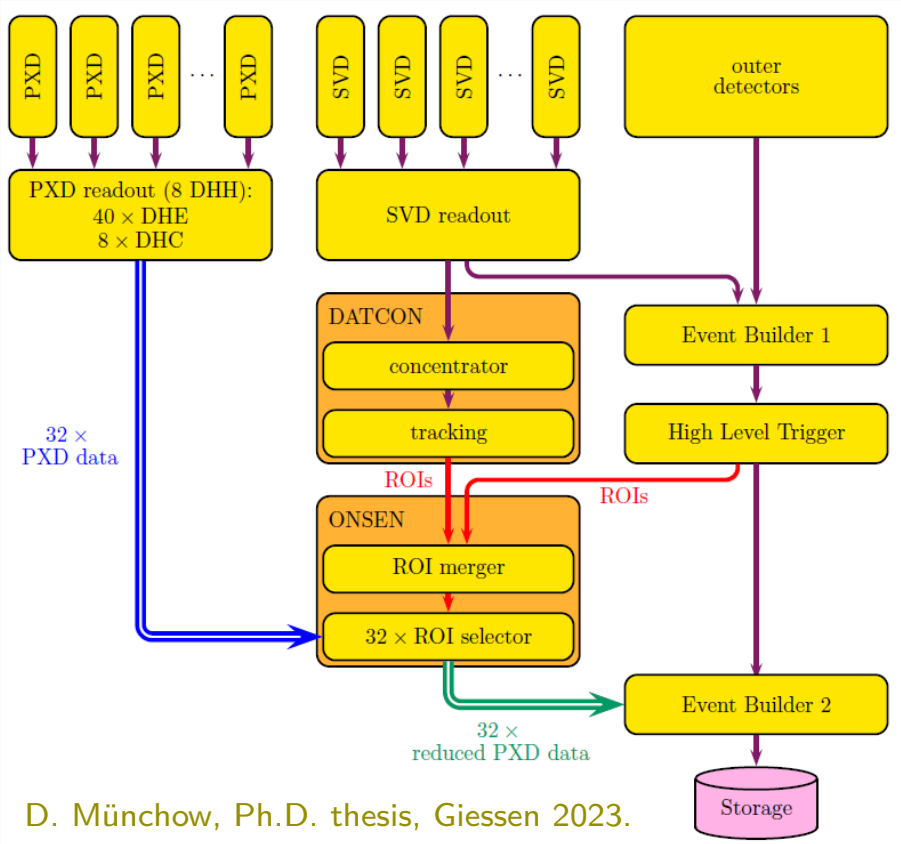
Justus-Liebig-Universität, Giessen, Germany

Belle II Germany meeting 2024, DESY.

Dataflow

PXD DAQ: requirements and solutions

- PXD frame rate 50 kHz (fixed), L1 trigger rate up to 30 kHz (factor 75 more than Belle);
- PXD generates about 10x more data than rest of Belle II: up to 20 GB/s at 3% occupancy; solution: optical links, 6 Gbps;
- Buffer PXD data until HLT decision, up to 5 seconds solution (mean: 1-2 seconds) solution: 4 GB RAM on FPGA board (only 1.5 GB are available for buffering);
- Apply ROI selection, ROIs are calculated by online tracking on HLT
  solution: logic on FPGA:
  - coordinate transformation;
  - paralysed up to 32 ROIs per module factor $\leq$355 faster than single core PC (Intel i7, 3.4 Ghz);
  - reduce data by factor $>$10;
- Send out data to event builder by 32 x Gigabit Ethernet links;
- Stable data taking about 10 months per year, 24/7 operation.

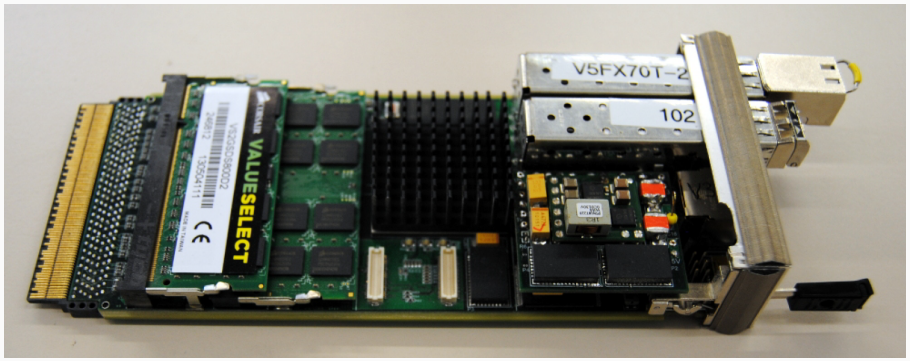


D. Münchow, Ph.D. thesis, Giessen 2023.

Hardware solution

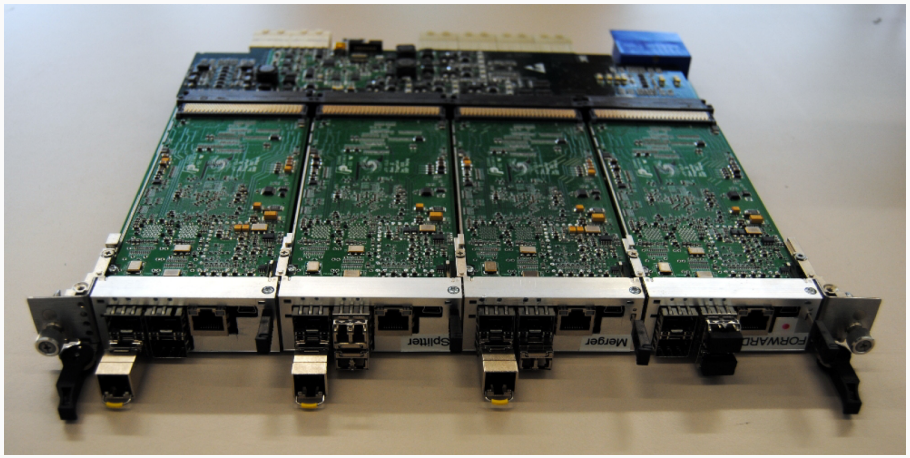
AMC card (IHEP Beijing, Giessen):

- Specifications:
  - v4.0 (final), 2017;
  - Virtex-5 FPGA;
  - 2 optical links (6.25 Gbps);
  - GbE;
- IPMI add-on boards (Mainz) for slow control and monitoring;
- 2 configurations and firmwares:
  - selector AMC;
  - merger AMC;



xTCA carrier card (IHEP Beijing, Giessen):

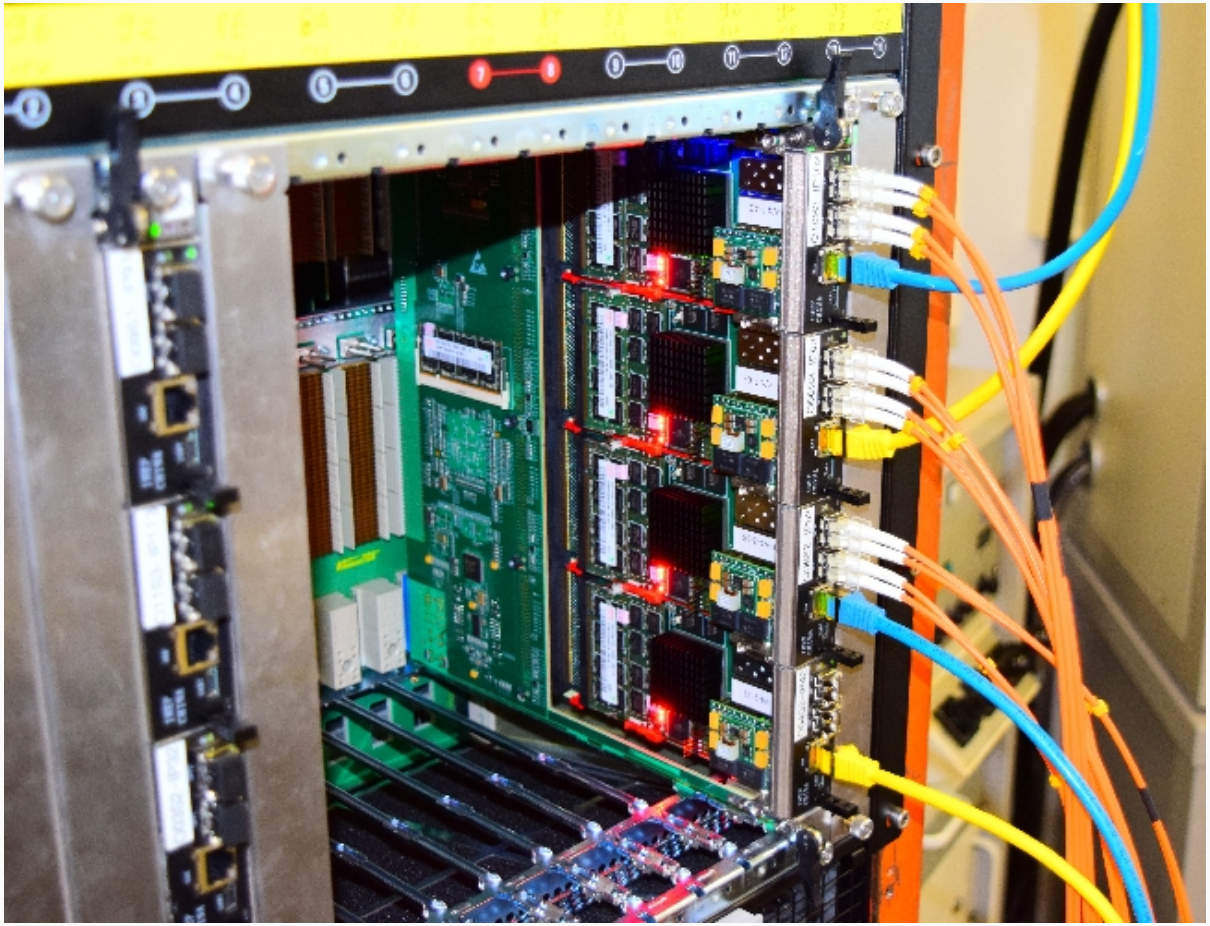
- Specifications:
  - v3.3 (final), 2017;
  - Virtex-4 FPGA;
  - GbE;
- add-ons:
  - RTM board;
  - power supply board;



Hardware solution

ATCA shelf:

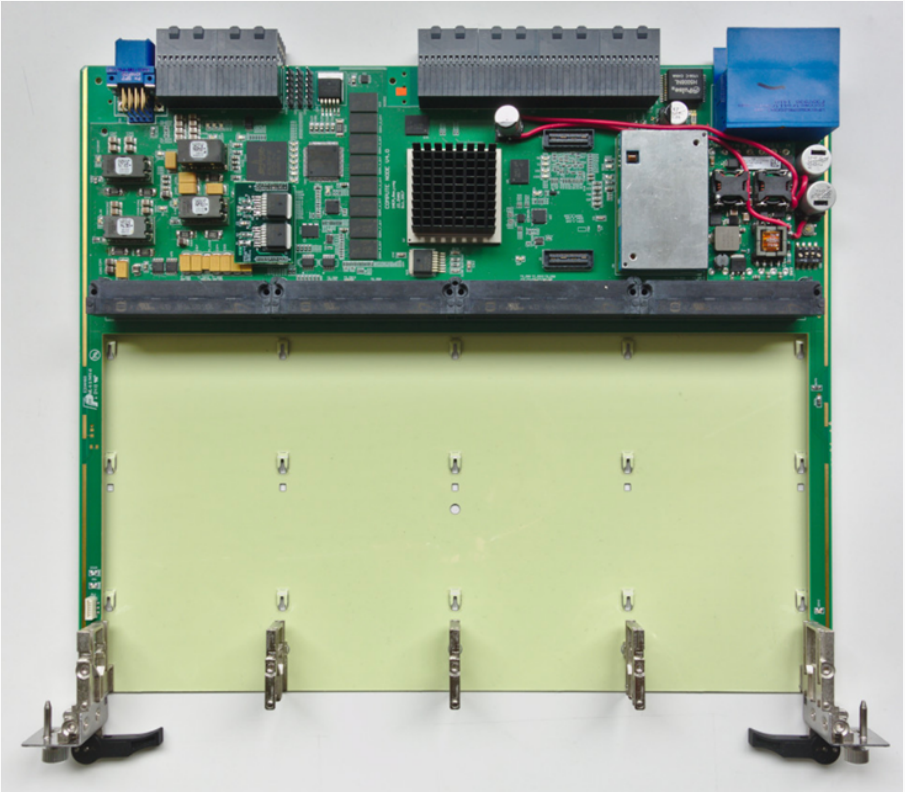
- Full-mesh backplane
- 14 slots for CNCBs
- In a given configuration, up to $\sim$ 1000 Gbps



Hardware solution

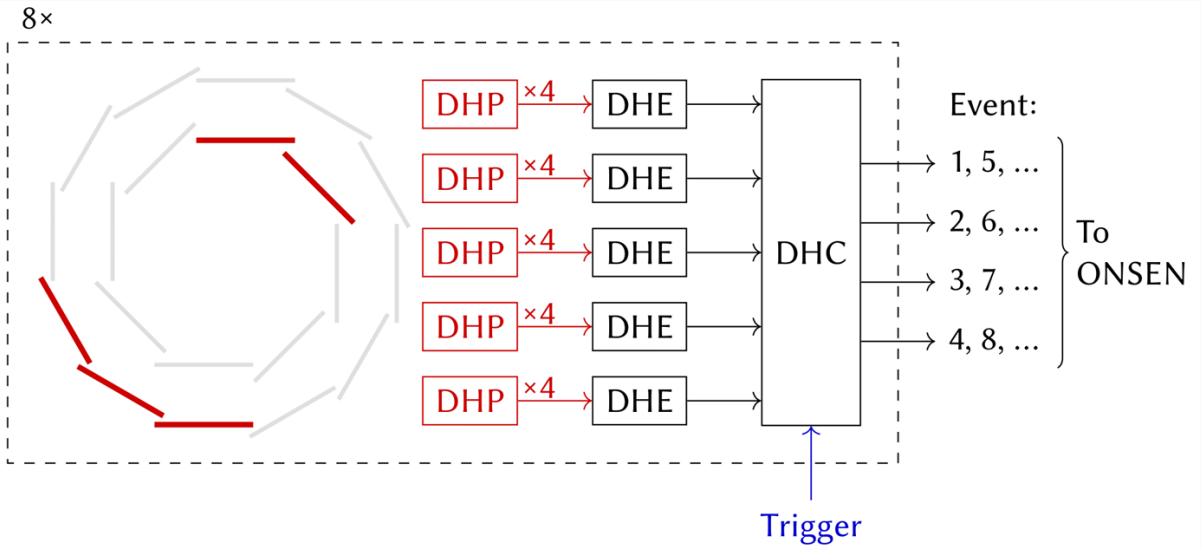
Spare parts:

- Spare AMCs are available in sufficient number;
- Not the case for carrier boards ($1 \rightarrow 0$ at KEK $+ 1$ in Giessen);
- New generation Kintex carrier board is being developed by M. Krein;
- Changes: new link protocol, no hard-core CPU anymore, programming by Vivado (planAhead for Virtex)
- Goal: AMC cards can be plugged and run identical firmware;
- Board was brought to KEK for testing inside ONSEN system, and back to Giessen. Problems (e.g. JTAG) were observed by Matthäus and are going to be investigated in November.



	Virtex-4 FX60 (CNCB)	Virtex-5 FX70T (xFP)	Kintex UltraScale 060 (Upgrade)
Registers	50k	44k	663k
LUTs	50k × 4-input	44k × 6-input	332k × 6-input
DSP Slices	128	128	2760
BRAM	4 Mb	5 Mb	38 Mb
MGT	16 × 6.5 Gbps	16 × 6.5 Gbps	32 × 16.3 Gbps
CPU	PPC405	PPC440	-

Connection to DHH

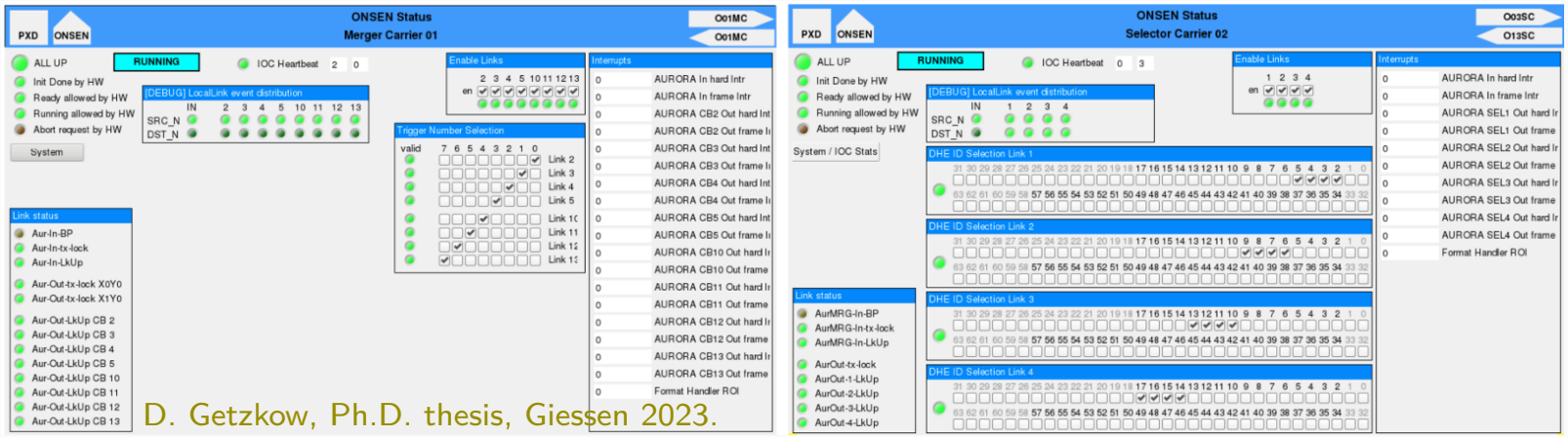


DHH components:

- Data Handling Processor (ASIC, Bonn)
- Data Handling Engine (FPGA, TU Munich)
- Data Handling Concentrator (FPGA, TU Munich)

Load balancing:

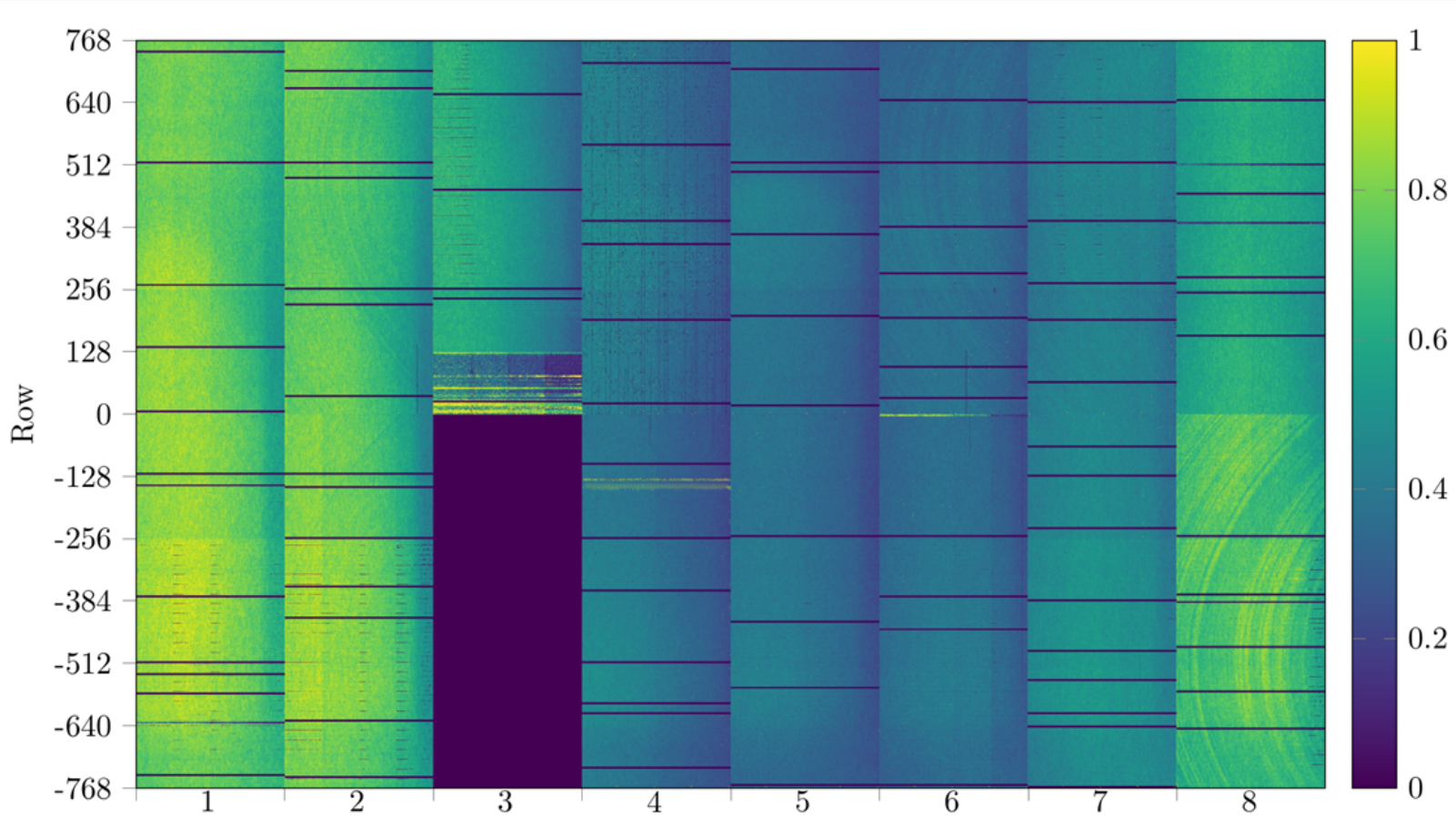
- Each DHC is processing data of 2 L1 and 3 L2 ladders (fixed configuration);
- DHC - ONSEN data transfer according to the round-robin algorithm (binary configurable);
- ROI fork, Trigger/Event ID and DHE ID (highly configurable).



D. Getzkow, Ph.D. thesis, Giessen 2023.

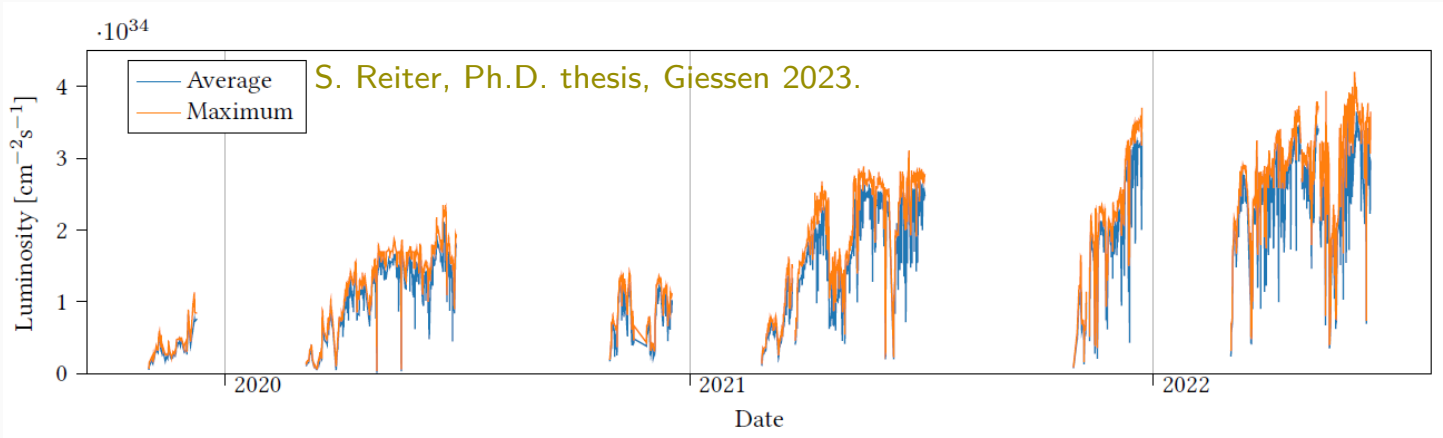
Performance

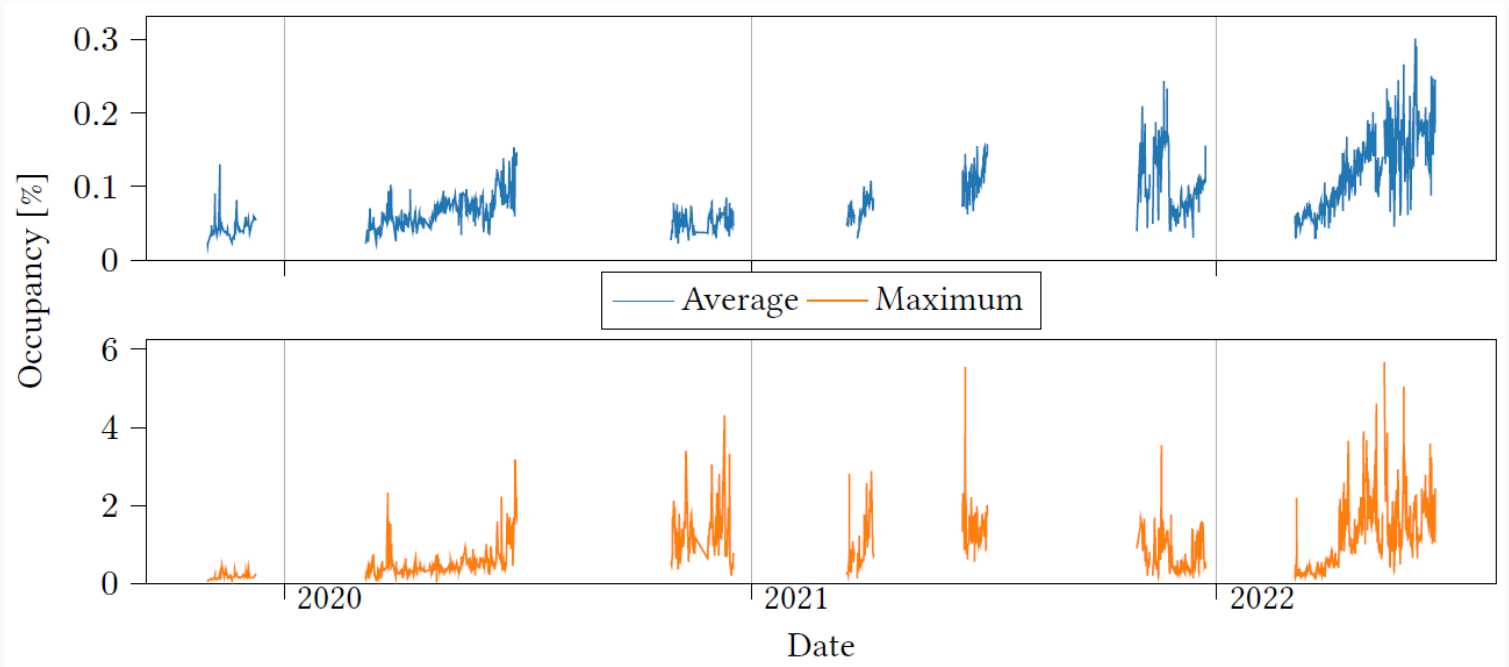
- Run1 (10.2019 – 06.2022):
  - 300 TB zero-suppressed data recorded (400+ million events)
  - Peak luminosity reached $4.7 \times 10^{34} \mathrm{cm}^{-2}\mathrm{s}^{-1}$ (x2 KEKB record)
  - Trigger rate up to 8 kHz (design 30 kHz, short tests run up to 35 kHz)
- Run2 (01.2024 – present):
  - x1.5 dataflow
  - Switched to the full setup — 8 carrier boards (only 4 were in use in Run1)



Occupancy

- Design average occupancy limit on the PXD DAQ is 2.5%
- Maximum tolerable instantaneous acceptance is limited to 12% by DHE

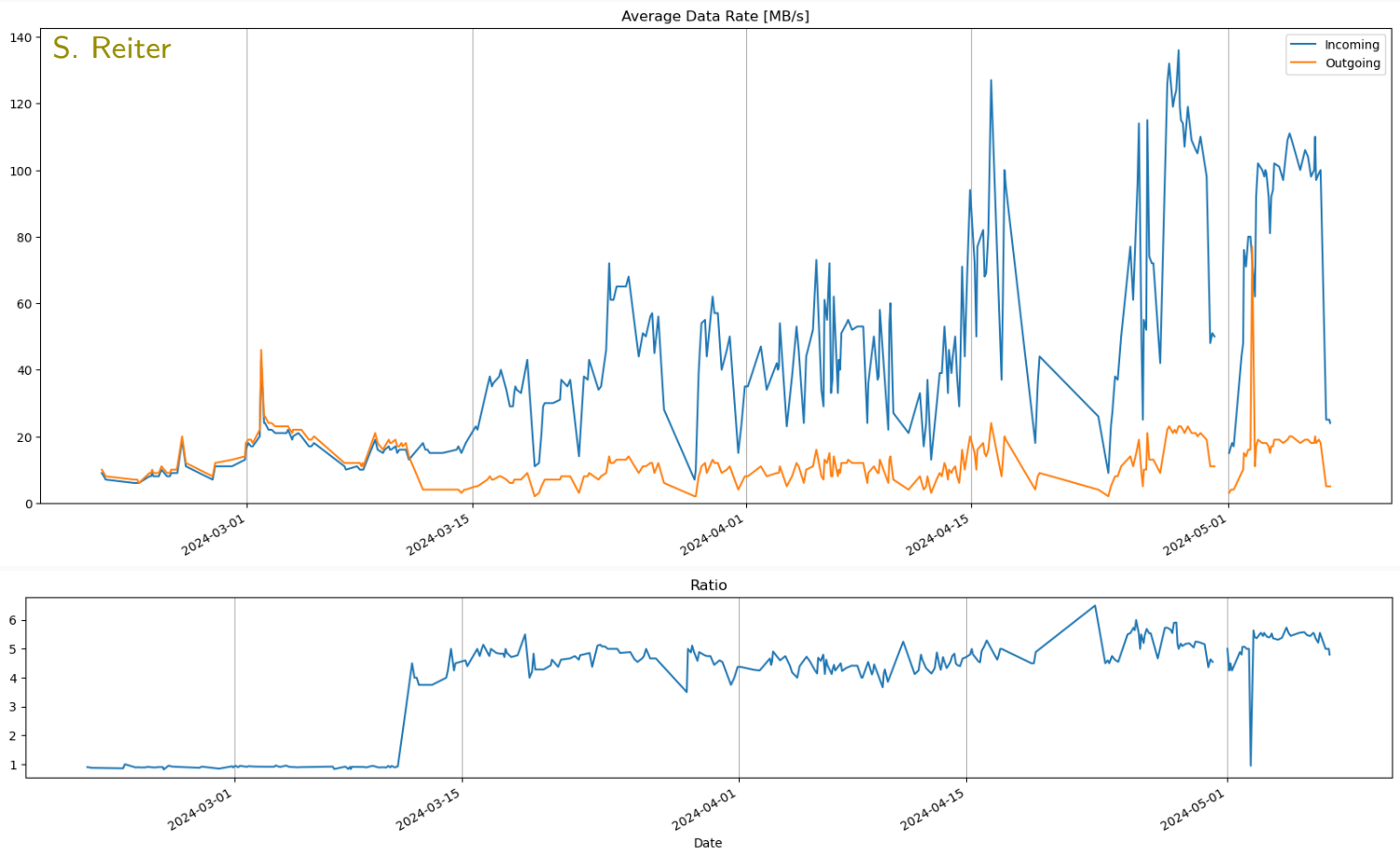




Data suppression

Event filtering:

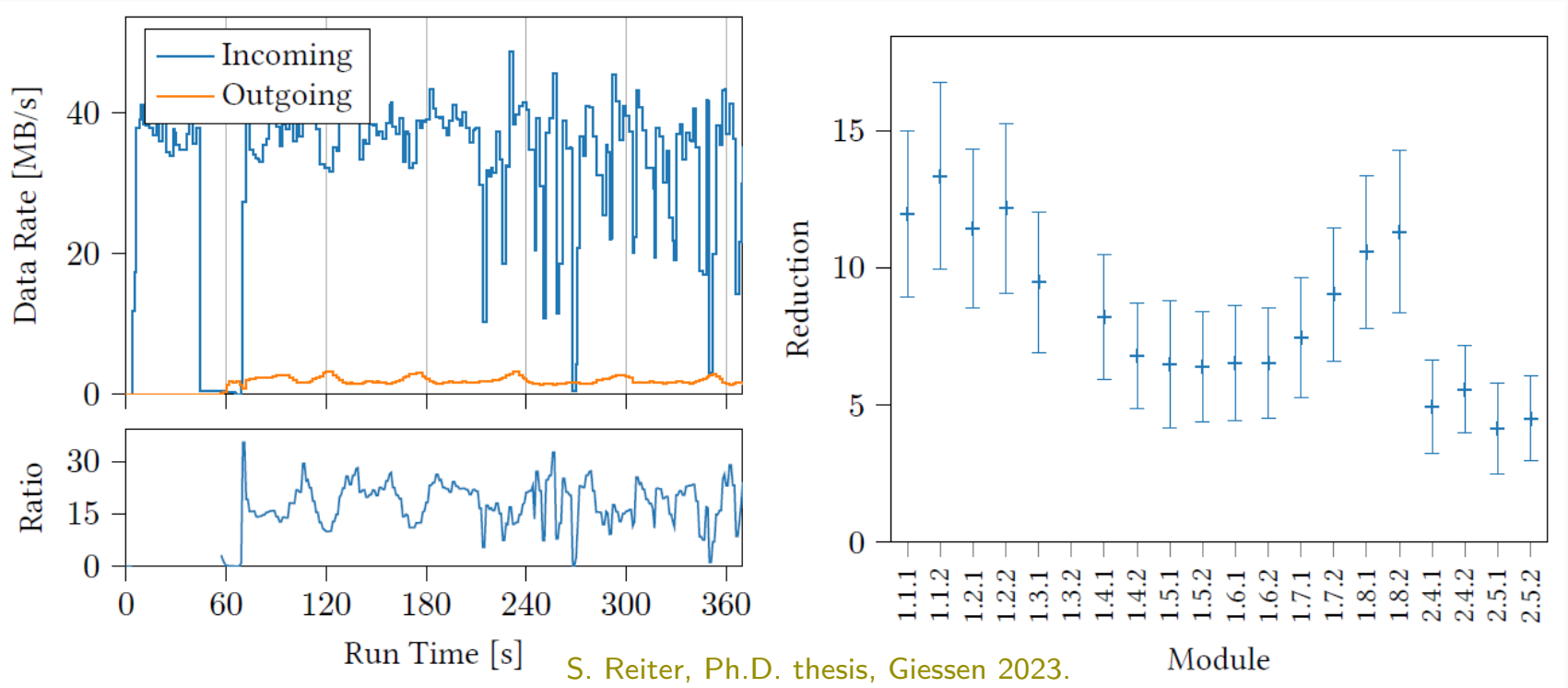
- HLT decision logic is used to classify events;
- Event filtering was enabled in 2021 (4.41 average reduction factor in phase 3)
- Maximum input rate 250 MB/s (2022)



Data suppression

ROI filtering:

- Extrapolation of SVD tracks is exploited to determine position of ROIs;
- Short test has been performed in 2019 for the zero-suppressed data;
- Suppression factor is in the 20-30 range, when both event and ROI filtering is enabled;
- Prediction of the combined suppression factor for different instantaneous luminosity and in different background conditions is not straight-forward;

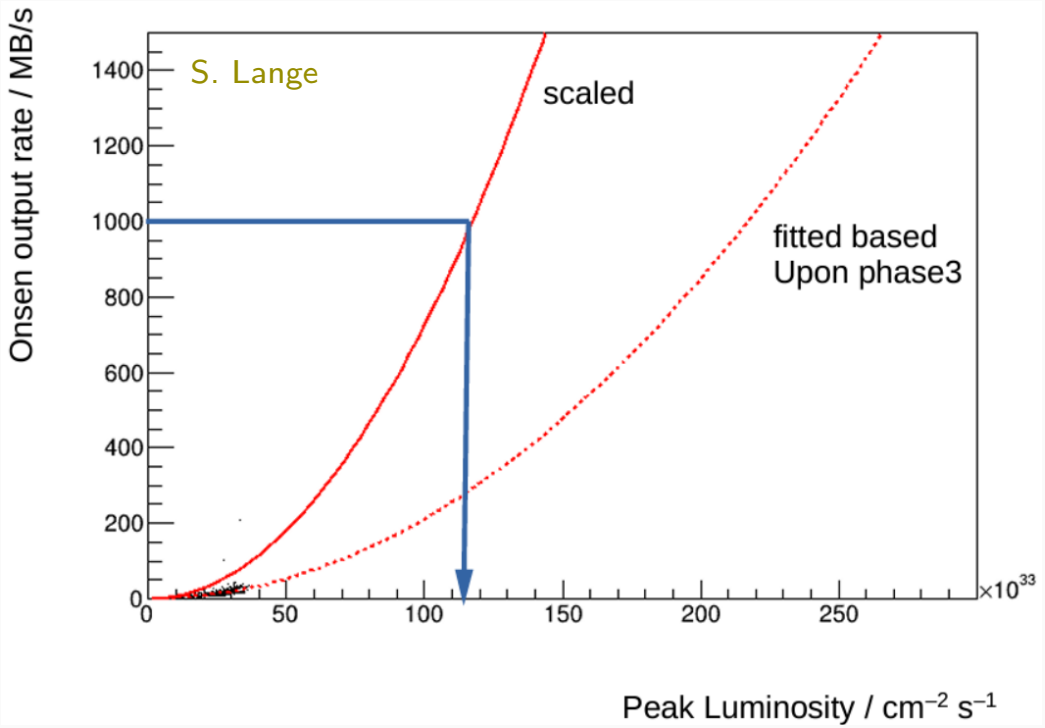


S. Reiter, Ph.D. thesis, Giessen 2023.

ROI selection forecast

Evaluation method:

1. Fit ONSEN output rate evolution;
2. Scale the fit function by the $S = S_{PXD2} \times S_{HLT}$ scale factor;
3. Find the $\mathcal{L}_{limit}$ (out $>$ 1000 MB/s);
4. Predict when it will be reached.



HLT scale factor (S_{HLT}):

- Avg. evt. filtering factor in phase 3: 4.41
- Avg. evt. filtering factor in the last week of phase 3: 5.53
- Phase 4 target evt. filtering factor: 3.00

$$S_{HLT} = 5.53/3.00 = 1.84$$

PXD2 scale factor (S_{PXD2}):

- Naively: x2 modules $\rightarrow$ x2 accumulated occupancy
- But: L2 modules have lower occupancy
- MC by B. Schwenker:

$$S_{PXD2} = 1.86$$

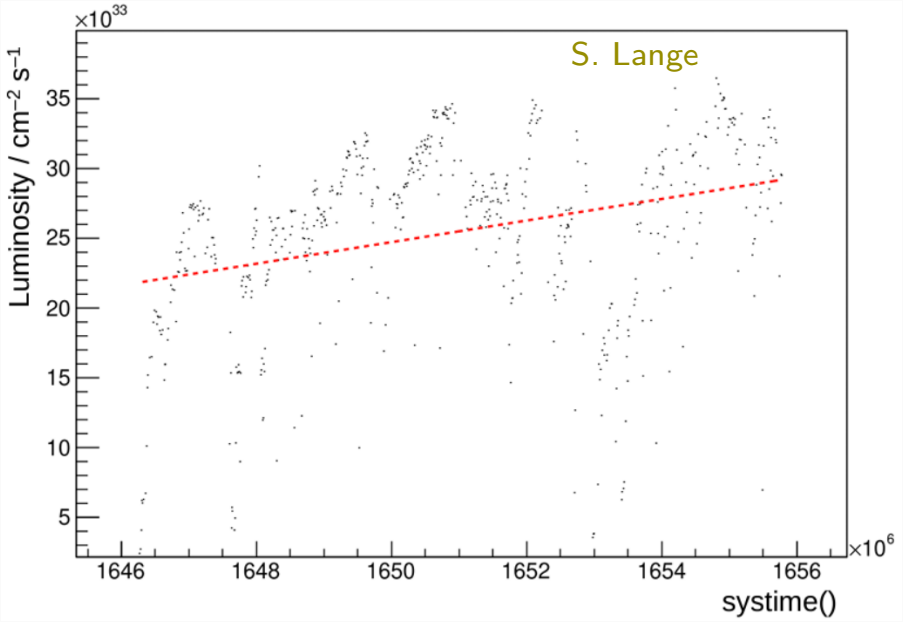
$$S = S_{PXD2} \times S_{HLT} = 1.84 \times 1.86 = 3.42$$

ROI selection forecast

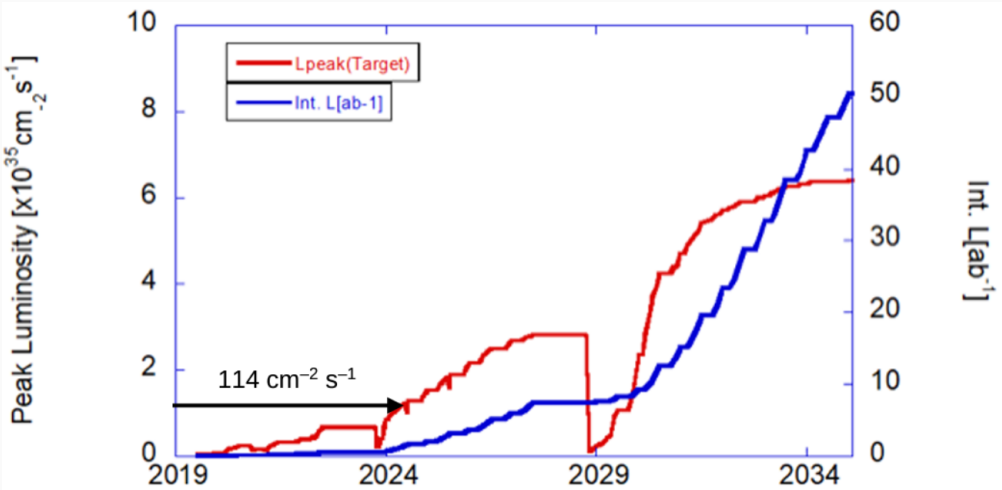
$$\mathcal{L}_{\text{limit}} = 1.14 \times 10^{35}\mathbf{cm}^{-2}\mathbf{s}^{-1}$$

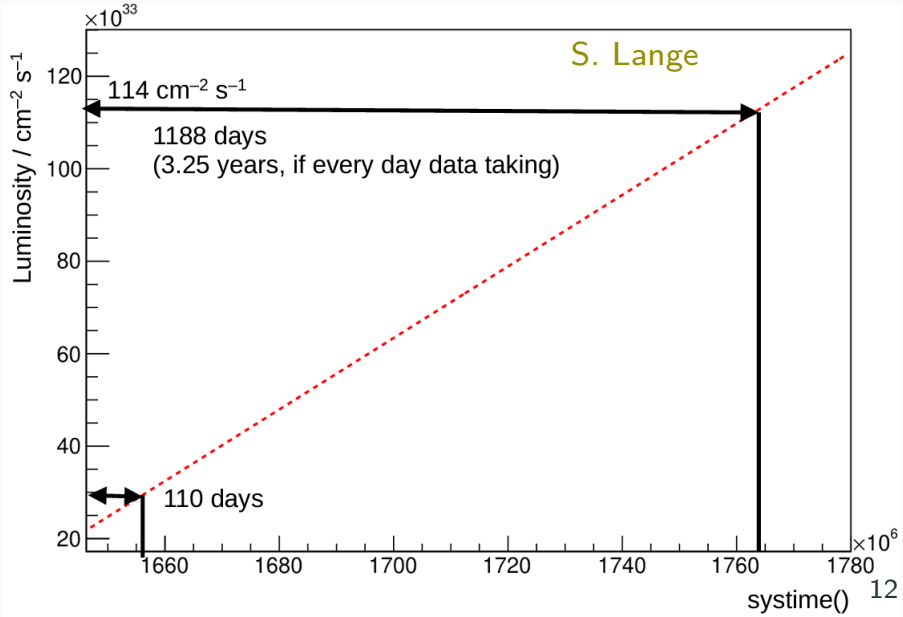
Note: Higher TRG rate is inbuilt in the fit function

Actual Belle II recorded luminosity



Official Belle II luminosity plot





DAQ stability

Stable data taking had and has the highest priority

There are two types of link problems:

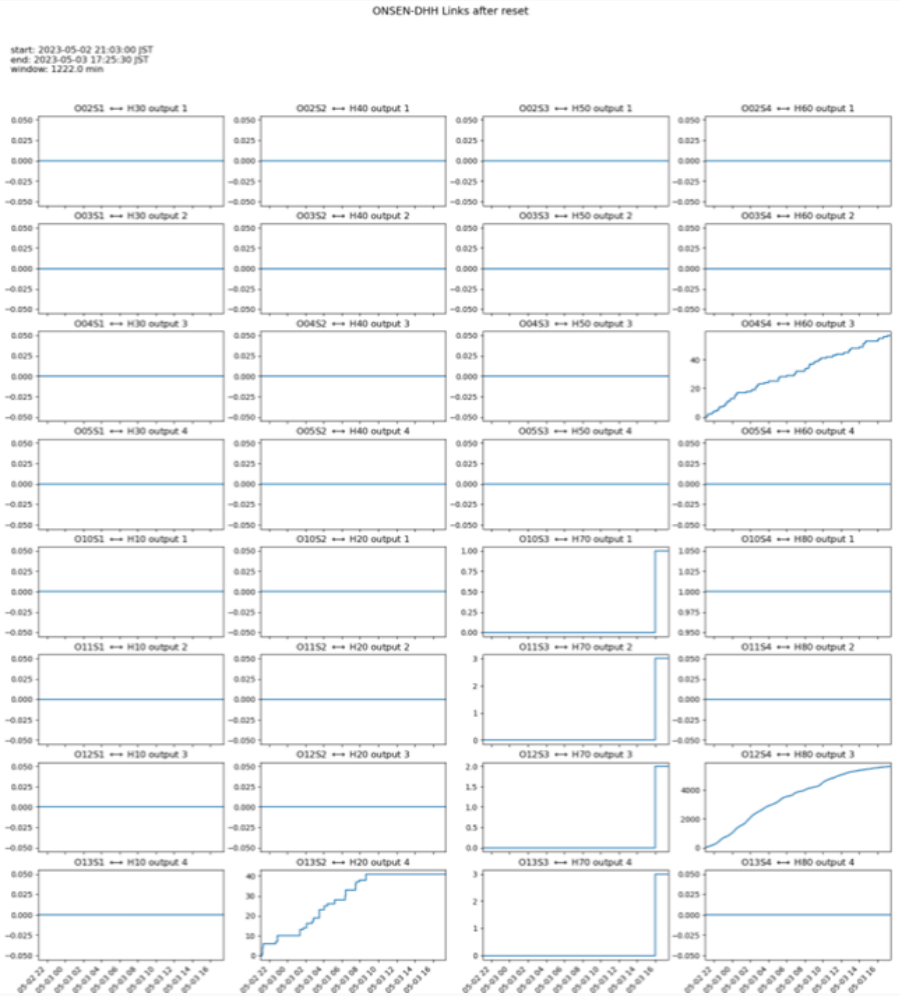
- Link drops (rare, 1 per day, but crashes DAQ)
- Link errors (not fatal, but worrisome)

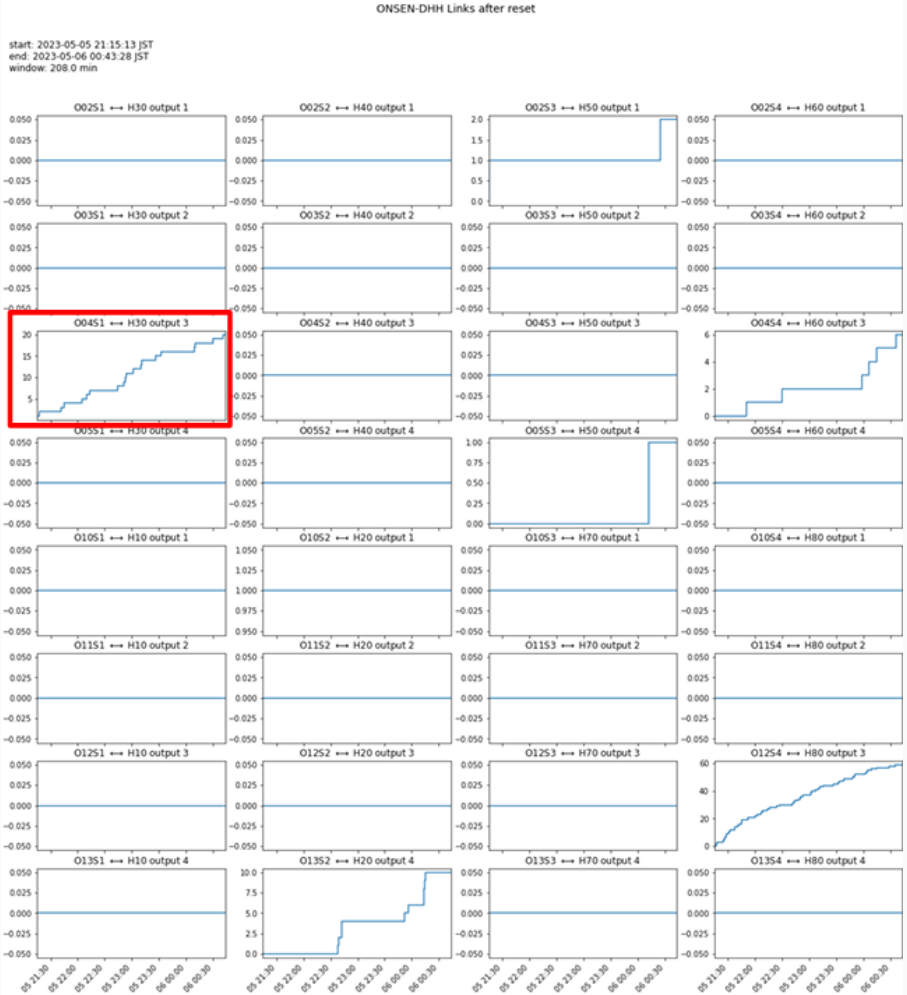
Details:

- 2023: `https://gitlab.desy.de/belle2/detector/pxd/commissioning/-/issues/5`
- 2024: `https://gitlab.desy.de/belle-ii-onsen/onsen/-/issues/188`
- ...

DAQ stability

- System evolution is observed
- E.g. the displayed link instability between 02.- and 05.05.2023





DAQ stability

Link errors summary:

- Observed persistently for one link only (ONSEN side: 13S2, DHH side: 20 7-8) Several AMC swaps suggest that the issue is not on the ONSEN side;
- This was the main reason for going from 6 Gbps to 3 Gbps;
- Only link drops, but no high link error rate observed;

Possible solutions:

- Long MPO fibre swapped on 11.06.2024 So far no long term test to see, if link drops still occur;
- Transceivers;
- DHH upgrade;

Link drops summary:

- Multiple AMC swaps have been performed;
- Currently the problem is constrained to 3 links: (12S2, 04S2, 04S3)
- 12S2 most critical ($\sim$2000 errors per hour)

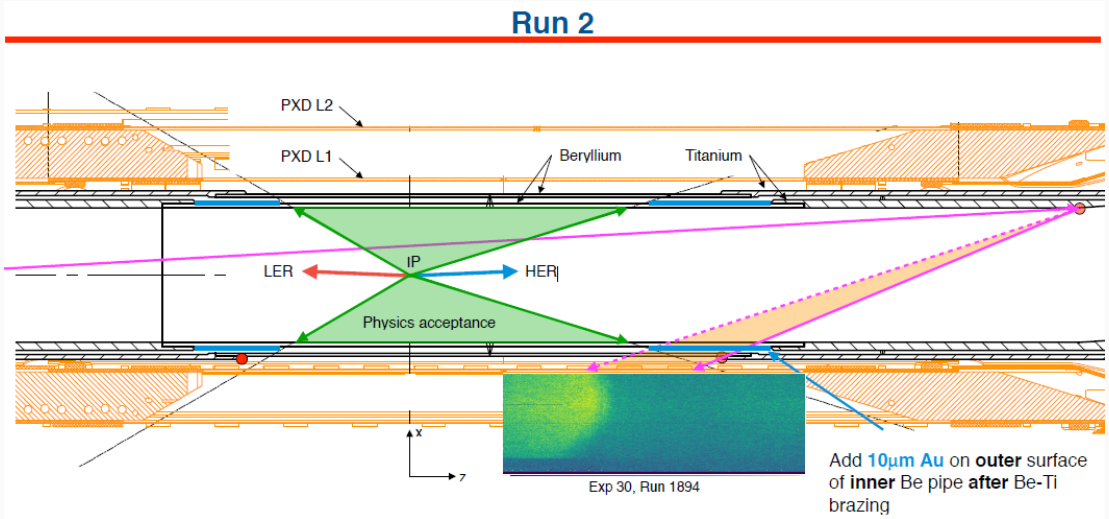
Possible solutions:

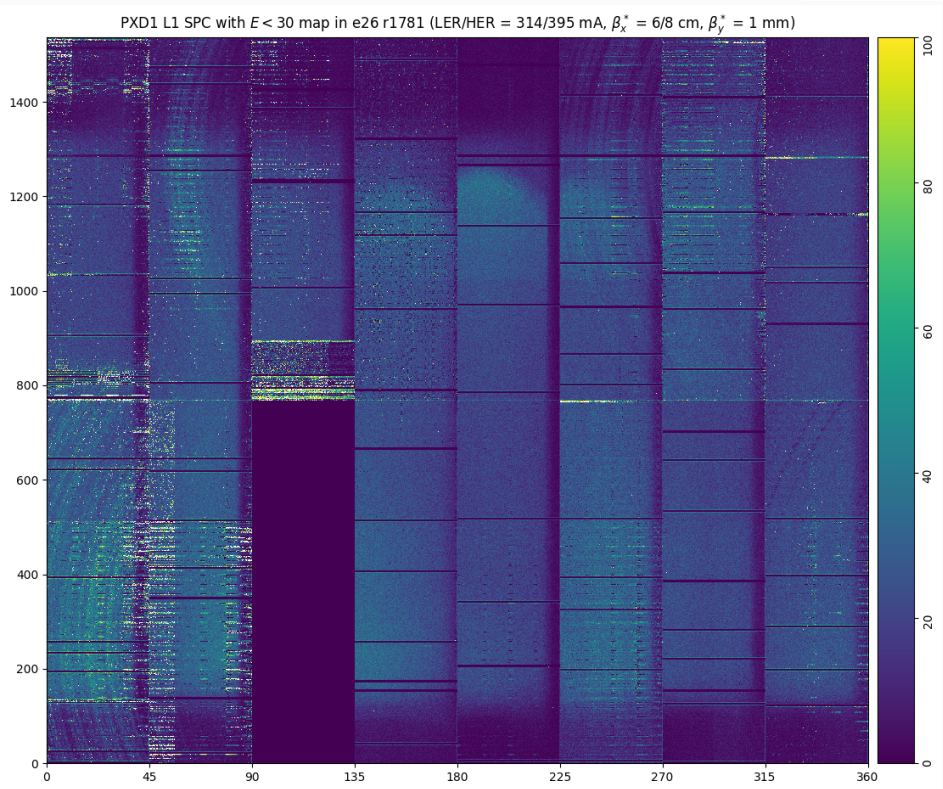
- Light yield has been measured for 12S2: lowest among all links
- Light yield measurement for the loop back test favours the problem on external side;
- Links cleaning didn't solve the issue entirely (factor 2 rate reduction);

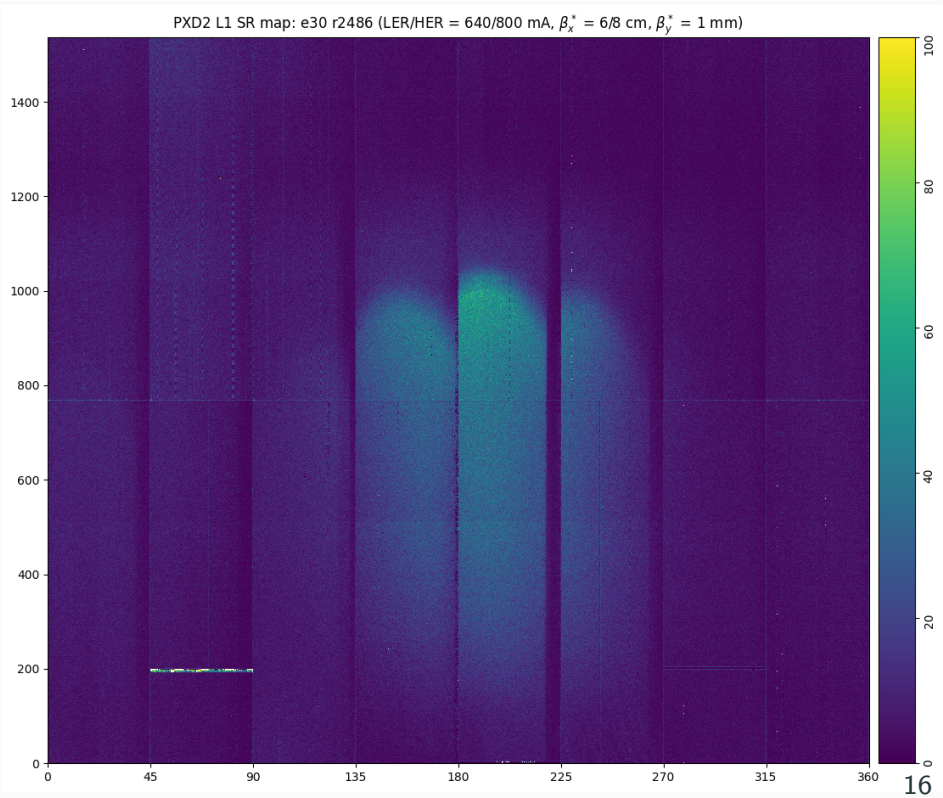
Running at 3 Gbps is not a long-term solution: might lead to readout loss at designed peak luminosity ($\sim$10% at 2.4% occupancy).

Synchrotron radiation in Run1 vs. Run2

- First observed on Dec 6 after HER optics change ($\beta_X^* = 8 \rightarrow 6$ cm);
- Origin: beam pipe backscattering;
- Not dramatic a.t.m., but might evolve as the beam is squeezed further.







Photon monitor

$N^{\mathrm{Tot}} \mathrel{+}= N \cdot \omega \cdot \mathrm{hF}$

$S^{\mathrm{Tot}} \mathrel{+}= \mathrm{pxlSize} \cdot \mathrm{pxlN} \cdot \omega$

$$I = \frac{N^{\mathrm{sig}}/S^{\mathrm{sig}}}{\mathrm{rF} \cdot N^{\mathrm{ref}}/S^{\mathrm{ref}}} = \left| n = N/S,\ \mathrm{hF}{=}\mathrm{rF}{=}\omega{=}1 \right| = n^{\mathrm{sig}}/n^{\mathrm{ref}}$$

N - number of hits

ω - area weight factor

hF - hitFactor

rF - referenceFactor

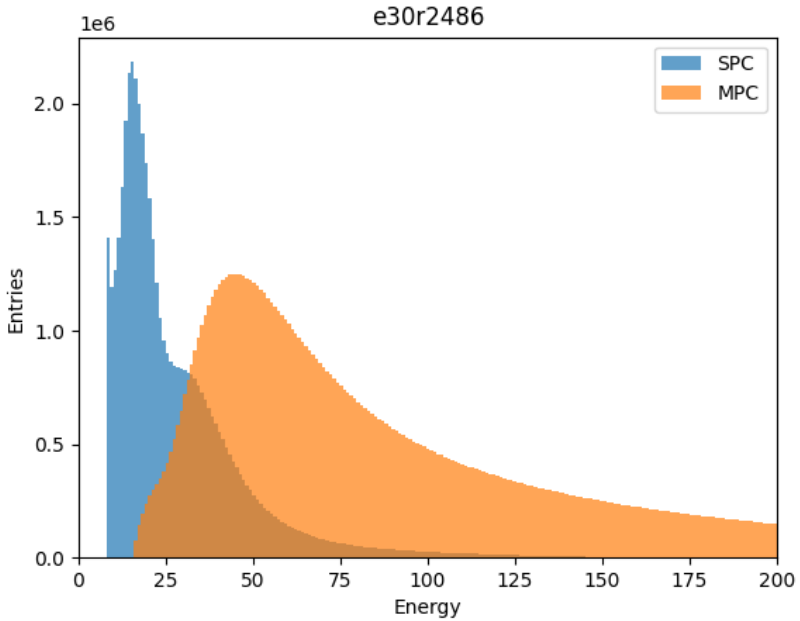
$I^{\mathrm{LE}}_{\mathrm{SPC}}$, $I^{\mathrm{HE}}_{\mathrm{MPC}}$

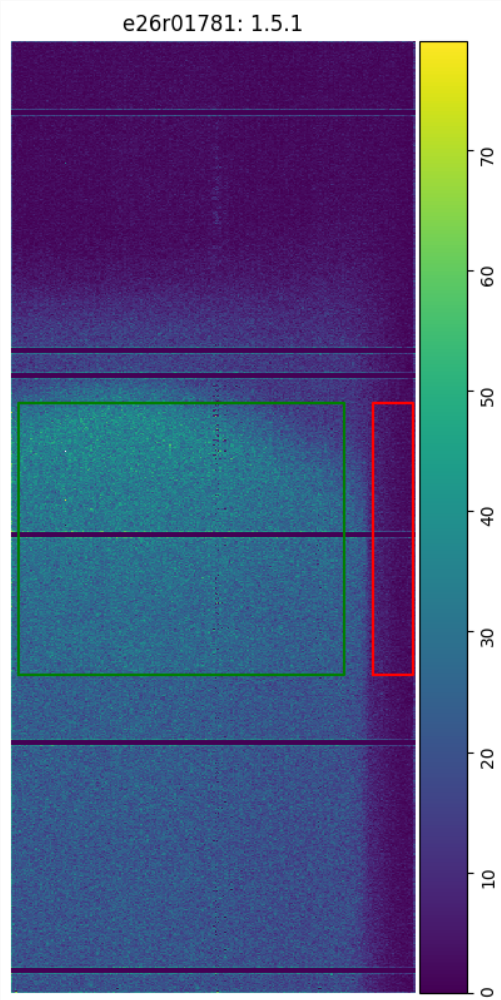
$$\mathrm{res} = \frac{I^{\mathrm{LE}}_{\mathrm{SPC}}}{I^{\mathrm{HE}}_{\mathrm{MPC}}} - 1 \begin{cases} \sim 0 & \text{good data} \\ > 3 & \text{high photon contamination} \end{cases}$$

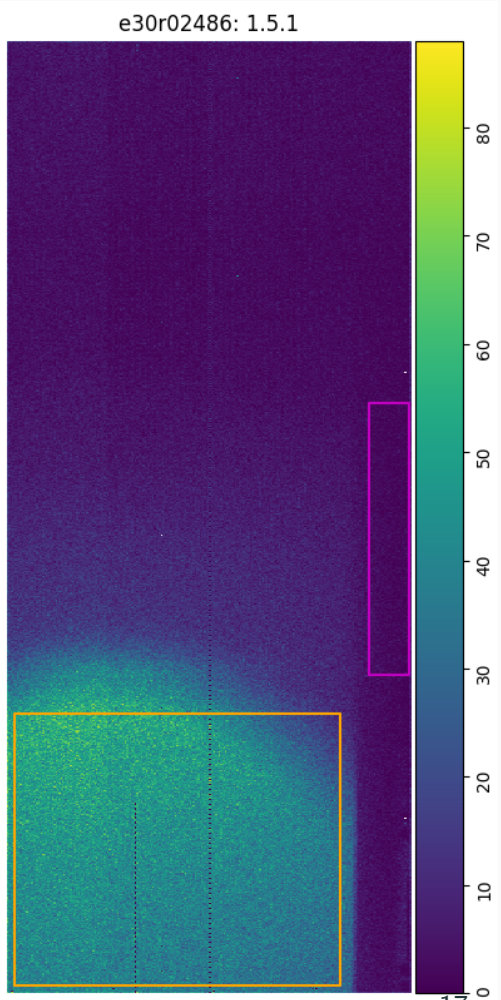
```
H1011:    res = 0.7
H1031:    res = 1.7
H1041:    res = 1.5
H1051:    res = 3.9
H1061:    res = 1.7
H1012:    res = -0.2
H1022:    res = -0.1
```

```
H1011:    res = 0.4
H1031:    res = 1.1
H1041:    res = 1.8
H1051:    res = 2.7
H1061:    res = 1.3
H1012:    res = 0.7
H1022:    res = 0.9
```

```
H1012:    res = 0.9
H1041:    res = 8.8
H1051:    res = 14.6
H1052:    res = 5.2
H1061:    res = 5.9
H1062:    res = 3.1
```







Summary

- ONSEN operation has proven overall stability in Run1;
- ONSEN is running in Run2 using factor 2 more hardware. Stable running until PXD2 was switched off;
- Spares depot is sufficient, but not abundant;
- Link stability challenges have risen after LS1:
  - Not critical for operation
  - Search for solutions is ongoing;
  - The upcoming hardware upgrade of the adjacent DAQ components will trigger further tests;
- ROI selection must be enabled, when Link from ONSEN to Event Builder reaches 1000 MB/s. 2026-2027? (depends on luminosity extrapolation of SuperKEKB)
- HOWTO documentation was extended, to be extended more in the future.